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Article (Published Version)

Driver, S P, Robotham, A S G, Bland-Hawthorn, J, Brown, M, Hopkins, A., Liske, J, Phillipps, S and Wilkins, S (2013) Two-phase galaxy evolution: the cosmic star formation histories of spheroids and discs. *Monthly Notices of the Royal Astronomical Society*, 430 (4). pp. 2622-2632. ISSN 0035-8711

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# Two-phase galaxy evolution: the cosmic star formation histories of spheroids and discs

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Accepted 2012 December 28. Received 2012 December 21; in original form 2012 July 13

## ABSTRACT

From two very simple axioms: (1) that active galactic nucleus activity traces spheroid formation, and (2) that the cosmic star formation history is dominated by spheroid formation at high redshift, we derive simple expressions for the star formation histories of spheroids and discs, and their implied metal enrichment histories.

Adopting a Baldry–Glazebrook initial mass function we use these relations and apply PEGASE.2 to predict the  $z = 0$  cosmic spectral energy distributions (CSEDs) of spheroids and discs. The model predictions compare favourably to the dust-corrected CSED recently reported by the Galaxy And Mass Assembly team from the far-ultraviolet through to the  $K$  band. The model also provides a reasonable fit to the total stellar mass contained within spheroid and disc structures as recently reported by the Millennium Galaxy Catalogue team. Three interesting inferences can be made following our axioms: (1) there is a transition redshift at  $z \approx 1.7$  at which point the Universe switches from what we refer to as ‘hot mode evolution’ (i.e. spheroid formation/growth via mergers and/or collapse) to what we term ‘cold mode evolution’ (i.e. disc formation/growth via gas infall and minor mergers); (2) there is little or no need for any pre-enrichment prior to the main phase of star formation; (3) in the present Universe mass loss is fairly evenly balanced with star formation holding the integrated stellar mass density close to a constant value.

The model provides a simple prediction of the energy output from spheroid and disc progenitors, the build-up of spheroid and disc mass and the mean metallicity enrichment of the Universe.

**Key words:** galaxies: bulges – galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: formation – galaxies: spiral – galaxies: star formation.

## 1 INTRODUCTION

The vast majority of galaxies can be adequately described as consisting of a compact smooth spheroidal component containing a predominantly pressure-supported old  $[\alpha/\text{Fe}]$ -enhanced stellar population, and/or an extended flattened star-forming disc component containing intermediate and young stars with a wide range in metallicities, having smooth rotation and embedded in an extensive gaseous cold gas disc. Exceptions exist, most notably the dwarf

populations which, while dominant in terms of number density, actually contribute only a modest amount to the baryon budget at the present time ( $<16$  per cent; Driver 1999; Geller et al. 2012). This dichotomy of galaxies into spheroids and discs has been known for over a hundred years stretching back to even before the confirmation that galaxies are external systems (e.g. Hubble 1926, 1936; Zwicky 1957, and references therein). To some extent this dichotomy has been recently ‘rediscovered’, through the statistical studies of large populations as a galaxy bimodality (Strateva et al. 2001; Baldry et al. 2004). Driver et al. (2006) argued that this bimodality is better interpreted in terms of the earlier bulge–disc dichotomy and advocated routine structural decomposition as vital (e.g. Allen et al.

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2006; Simard et al. 2011; Lackner & Gunn 2012) to directly trace the independent evolutionary histories of the spheroidal and disc components.

Numerical models of galaxy formation struggle to produce realistic galaxy systems with a tendency to form overly cuspy cores and difficulty in maintaining extended disc structures with a high axis ratio (White & Navarro 1993; Navarro & Steinmetz 2000; Abadi et al. 2003; House et al. 2011). Both problems are likely to be connected to the different fundamental properties of the dark matter and the baryons, and in particular their ability to experience pressure and their ability to dissipate energy. In the core regions the gravitational coupling of the baryons with the dark matter may allow it to exhibit a pseudo-pressure, whereas in the outer regions the ability of the baryons to dissipate energy on a time-scale which is faster than the free-fall time-scale may allow for the formation of a thin rotating baryonic disc. This picture while simple to articulate has proven extremely hard to simulate, with the need to partition and redistribute the angular momentum in a quite specific manner to result in galaxies with realistic appearances. In particular merger events are extremely disruptive to this process, imparting both energy and angular momentum to the baryonic disc, which is easily disrupted or ‘plumped up’ (see Barnes & Hernquist 1992, for extensive discussion and early references on this topic, also Hopkins et al. 2009, for updated simulations on the survivability of discs during merger events). In general the greater the merger rate, the more bulge dominated the final galaxy population appears.

More contemporary hydrodynamical simulations (e.g. Agertz, Teyssier & Moore 2011; Governato et al. 2010; Scannapieco et al. 2011; Domenech-Moral et al. 2012) are now starting to show significant success at producing realistic ‘looking’ bulge–disc systems by incorporating a greater level of cold gas infall than previously assumed, as argued earlier by Keres et al. (2005) and Dekel et al. (2009). These focused hydrodynamical studies, however, are inevitably extracted from numerical simulations with particularly quiescent merger histories, suggesting such systems should be the exception rather than the norm. Hence, while numerical simulations of the development of the dark matter haloes find a continual process of halo merging, it appears that the baryons and what we identify as galaxies (baryonic condensates), might not develop in the same way. Martig & Bournaud (2010) argued that feedback from low- and intermediate-mass stars can contribute significantly to the redistribution of mass from the bulge to the disc through extensive (or even excessive) mass loss. This baryonic outflow could help alleviate the problem of excessive bulge formation by allowing some fraction of the collapsed stellar mass (up to  $\sim 50$  per cent), to return to the halo and contribute to the later growth of a disc – thereby coupling bulge and disc growth. However this mechanism also relies on a fairly quiescent merger history during later times, and does not easily explain the broad diversity of bulge–disc ratios seen. As an aside, simulations have also demonstrated that baryonic outflows from the core regions can help provide a plausible explanation to the core-cusp problem (Governato et al. 2012; Zolotov et al. 2012). Clearly feedback and infall are both crucial processes, whose motivation is as much driven by the requirement to produce realistic looking images as by fundamental physics, and which are both more effective if the merger rate is either low or at least confined to earlier epochs.

As argued in the opening paragraph, we advocate a more heuristic approach where we put aside the issue of dark matter assembly and start by asking whether the dichotomy of galaxy structure is best explained by two distinct formation mechanisms. Following the earlier discussion and lessons learnt from the simulations, the

obvious two mechanisms can loosely be termed as a hot and cold mode. In the hot mode spheroids are formed early and rapidly via dynamically hot (turbulent) processes (collapse, fragmentation and merging). In the cold mode discs are formed more slowly, from an extended quiescent phase of cold gas infall regulated by internal feedback (i.e. supernova). This basic concept is of course not new (e.g. Larson 1976; Tinsley & Larson 1978, see also Granato et al. 2001; 2004 and Lapi et al. 2006) but has laid dormant for some-time overshadowed by the dominance of merger-driven evolution. However the revival is also being championed via a series of semi-analytic studies by Cook, Lapi & Granato (2009) and Cook et al. (2010a,b, see also Dekel et al. 2009) inspired by behaviour seen in numerical simulations in which an initial rapid hot merger phase is typically followed by a more quiescent phase of accretion (see also L’Huillier, Combes & Semelin 2012).

The two-phase model is both obvious (given the bulge–disc nature of galaxies) and controversial, as it marginalizes the merger rate required for dark matter assembly to earlier epochs than simulations typically suggest. This low merger rate is arguably corroborated by the local studies of dynamically close pairs (in particular see Patton et al. 2002; De Propriis et al. 2005, 2007, 2010) – although a correct derivation of the merger rates requires a robust understanding of the merger time-scales, which are currently poorly constrained. Perhaps more compelling, however, is the result that only 40 per cent of the present day stellar mass resides in spheroidal systems (Driver et al. 2008; Gadotti 2009; Tasca & White 2011). A key inference is then: *if discs are destroyed/thickened during mergers, yet the majority of stellar mass resides in discs, the dominant formation mechanism cannot be merger driven, but presumably the more quiescent process of cold gas accretion.* This statement becomes more profound when one realizes that the stellar mass in discs today only measures that unaffected by mergers, and that some of the stars currently in spheroidal systems may have originally formed within discs via cold accretion prior to a merger event. In some bulge formation scenarios, star formation via merging is dispensed with altogether and replaced by the migration of massive star formation clumps formed within deeply turbulent discs (e.g. Elmegreen, Bournaud & Elmegreen 2008). This potentially relegates the stellar mass build-up driven by mergers to be in the 0–40 per cent range by mass. Clearly mergers do occur at all redshifts and similarly discs may form, be disrupted, and reform at any redshift. Recently L’Huillier et al. (2012) reported that 77 per cent of a galaxy’s mass is formed via gas accretion and 23 per cent via direct merging from simulations. Other empirical studies also seem to suggest that the bulk ( $\sim 70$  per cent) of the stellar mass is mostly assembled by  $z \sim 1$ , again marginalizing the role of late time major mergers (e.g. Bundy et al. 2004; Brown et al. 2007, 2008).

Focused studies of nearby galaxies are also unveiling significant levels of gas accretion in some nearby systems (Sancisi et al. 2008) and studies of the very rapid evolution of galaxy sizes have argued (e.g. Graham 2011) that the compact elliptical systems seen at intermediate redshift ( $1.4 < z < 2.5$ ) by Daddi et al. (2005) and Trujillo et al. (2006) (see also Bruce et al. 2012) might represent the naked bulges of present day spiral systems.

In essence the two-phase model is an attempt to highlight, conceptually, the possibility of a distinct change in the primary galaxy formation mechanism occurring at some transition redshift from an era where the *dominant* mode is major mergers leading to spheroid formation, to an era where the *dominant* mode is accretion leading to disc formation.

At early cosmic epochs we see a prevalence of distinct phenomena, in particular highly asymmetrical morphology in

massive/luminous systems (Driver et al. 1998; Conselice, Blackburn & Papovich 2005; Ravindranath et al. 2006) and significantly increased active galactic nucleus (AGN) activity (Fan et al. 2001, 2003; Croom et al. 2004; Richards et al. 2006). AGN activity is directly linked to the formation and growth of the associated super-massive black holes (SMBH; Hopkins et al. 2008) which in turn is linked to spheroid formation via the well established SMBH–bulge relations [see e.g. the review by Ferrarese & Ford 2005 or the recent near-infrared (IR) SMBH–bulge luminosity relation by Vika et al. 2012]. Recent studies also argue, from more direct empirical evidence, that AGN activity is almost always coincident with massive star formation and that the two processes do indeed appear to occur hand-in-hand (e.g. Rafferty et al. 2011). This AGN–SMBH–bulge connection therefore implies a clear time-scale for the formation of the spheroid systems (see also Pereira & Miranda 2011 for a similar argument, albeit applied in the opposite direction).

In Section 2 we describe the  $z = 0$  empirical data describing the cosmic spectral energy distribution (CSED) of spheroids and discs as recently reported by the Galaxy And Mass Assembly (GAMA) team (Driver et al. 2011, 2012). In Section 3 we take the above arguments to their natural conclusion and use the AGN–SMBH–bulge connection to define the independent star formation history of spheroids and assign the residual star formation, implied by the cosmic star formation history (CSFH), to describe that of the discs. In Section 4 we use our star formation histories to produce predictions of the CSED of spheroids and discs, and in Section 5 compare the predictions to the data.

Throughout we use  $H_0 = 70 h \text{ km s}^{-1} \text{ Mpc}^{-3}$  and adopt  $\Omega_M = 0.27$  and  $\Omega_\Lambda = 0.73$  (Komatsu et al. 2011).

## 2 THE $z = 0$ COSMIC SPECTRAL ENERGY DISTRIBUTION

In Driver et al. (2012) we reported the empirical measurement of the CSED in the nearby Universe, corrected for dust attenuation, and spanning the wavelength range from 0.1 to 2.1  $\mu\text{m}$ , i.e. the regime over which direct stellar light dominates. These data were derived from the combination of the GAMA spectroscopic survey, currently underway on the Anglo-Australian Telescope (Driver et al. 2011), coupled with reprocessed and aperture matched data from *Galaxy Evolution Explorer* (GALEX), Sloan Digital Sky Survey (SDSS) and United Kingdom Infrared Telescope (UKIRT) Large Area Survey (LAS; see Hill et al. 2011; Seibert et al., in preparation). Driver et al. (2012) also provided the CSED subdivided according to spheroid-dominated and disc-dominated systems. The division into spheroid and disc dominated was achieved via visual classification, as neither a simple colour nor Sérsic index division appears to cleanly separate the two populations (see also Kelvin et al. 2012, fig. 20).

The sample originated from a common volume of  $2.8 \times 10^5 (\text{Mpc } h^{-1})^3$  over the redshift range  $0.013 < z < 0.1$ . Although the GAMA survey currently contains about 180 000 galaxies with known redshifts, the adopted redshift range significantly reduces the sample size to around 10 000. It also simplifies and removes any luminosity bias arising from large-scale clustering as the sample is pseudo-volume limited around the  $L^*$  region – i.e. those galaxies which dominate the luminosity density measurements.

As the GAMA survey lies entirely within the SDSS, the GAMA CSED was renormalized to the full SDSS survey area. This reduces the cosmic/sample variance from around 15 to 5 per cent (using the formula for estimating cosmic variance given by equation 4 of Driver & Robotham 2010).

### 2.1 The CSED of spheroids and discs

The final CSED values we use here are the spheroid dominated and *attenuation-corrected* disc-dominated values taken directly from table 7 of Driver et al. (2012).

As dust attenuation is such a crucial issue it is worth mentioning the genesis of the corrections used by the GAMA team. First, the dust correction is only applied to the disc-dominated data and the spheroid population is assumed dust free (e.g. Rowlands et al. 2012). Secondly, the corrections are based on the radiative transfer models of Tuffs et al. (2004) and Popescu et al. (2011) which have been fine-tuned to the multiwavelength [far-ultraviolet (FUV)–far-IR] data of NGC 891, and incorporate three distinct dust components: an extended low-opacity disc; a compact high-opacity disc and dust clumps. This fiducial model is calibrated to the galaxy population at large by modifying the  $B$ -band central face on opacity until the predicted variation of flux with inclination matches the trend of  $M^*$  with inclination seen in the Millennium Galaxy Catalogue (MGC) data (Driver et al. 2007). This calibrated model was then used to derive the combined face-on and inclination dependent correction for a population of galaxies averaged over all viewing angles and over a wavelength range of 0.1–2.1  $\mu\text{m}$  (Driver et al. 2008). This photon escape fraction (varying from 24 per cent in the FUV to 89 per cent in the  $K$  band) was then used to correct the CSED of disc-dominated systems to the intrinsic CSED, which we use here.

The CSED of spheroid-dominated and disc-dominated galaxies, however, is not precisely what we require, as some proportion of the CSED flux in the disc-dominated class may be coming from the central bulges. Likewise, some proportion of the flux in the spheroid-dominated class may be due to faint discs. In order to assess how much of a problem this might be, we can compare the ratio of the  $K$ -band luminosity densities of the spheroid-dominated to non-spheroid-dominated samples, to the ratio of the stellar mass densities of bulge+elliptical systems to disc systems from Driver et al. (2007).<sup>1</sup> This test assumes that the  $K$ -band luminosity is a suitable single-band proxy for stellar mass. We find reasonable agreement (within 12 per cent), suggesting that a comparable amount of flux needs to be redistributed in either direction. In detail, the  $K$ -band luminosity densities are 1.2 and 2.2 ( $\times 10^{34} h \text{ W Mpc}^{-3}$ ) for the spheroid-dominated and non-spheroid-dominated populations, respectively (taken from table 7 of Driver et al. 2012). Meanwhile the stellar mass densities for spheroids (bulge+ellipticals) and discs are 2.9 and 4.7 ( $\times 10^8 h \text{ M}_\odot \text{ Mpc}^{-3}$ ), respectively (taken from table 1 of Driver et al. 2007). This gives agreement to  $\sim 10$  per cent and suggests that for the moment we can adopt the following approximation:

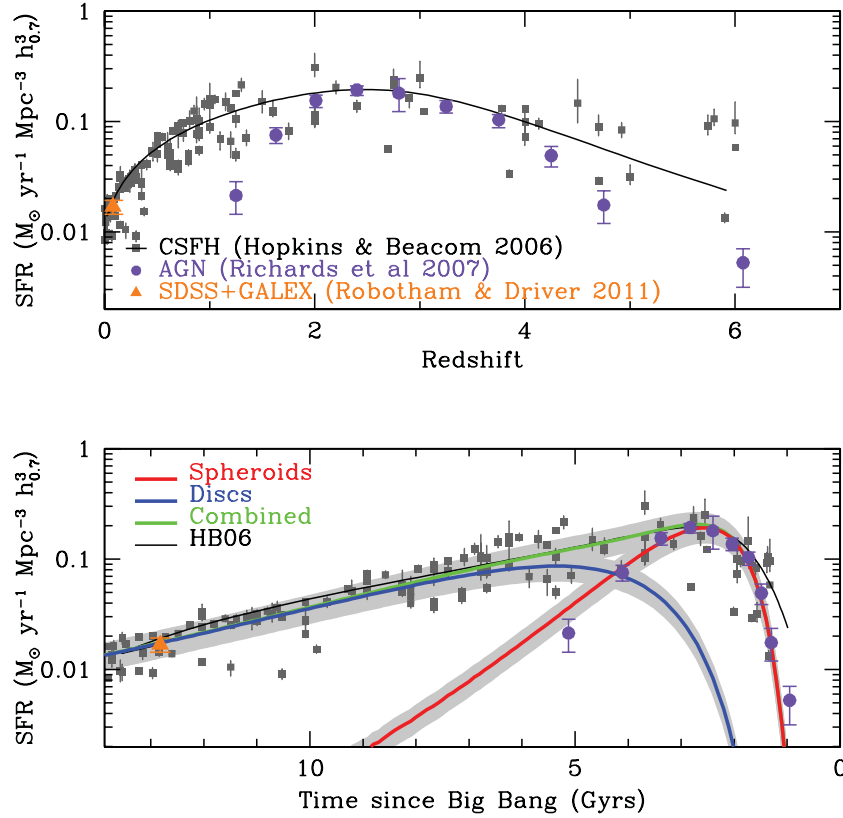
$$\begin{aligned} \text{elliptical+bulge CSED} &\approx \text{spheroid-dominated CSED}, \\ \text{disc CSED} &\approx \text{non-spheroid-dominated CSED}. \end{aligned}$$

In due course all galaxies at  $z < 0.1$  in the GAMA survey will be decomposed into bulge and disc components to enable a direct derivation of the true spheroid and disc CSEDs.

## 3 THE STAR FORMATION HISTORY OF SPHEROIDS AND DISCS

The local CSED should be a predictable quantity if the CSFH is known, the initial mass function (IMF) is universal and known, and

<sup>1</sup> The Driver et al. (2007) study is based on bulge–disc decompositions of the MGC data (Liske et al. 2003; Driver et al. 2005) described in full in Allen et al. (2006).



**Figure 1.** Upper panel: the CSFH from Hopkins & Beacom (2006, table 2) (black line) and the actual data (grey points) calibrated to a modified Salpeter IMF (see Table 1). Overlain are the quasi-stellar object (QSO) luminosity density data from Richards et al. (2006, fig. 20). The QSO luminosity density is scaled until the peak aligns with the peak of the CSFH. Lower panel: the same data but now shown with the ordinate in units of age. Overlain are our parametric fits to these data which provide our inferred CSFHs for the spheroid and disc systems. On both panels we also show the star formation rate (SFR) derived from the SDSS/GALEX FUV luminosity function given in Robotham & Driver (2011) converted to a modified Salpeter A IMF (see Table 1 or Hopkins & Beacom 2006).

a plausible stellar evolution code applied. Of course this is not quite so simple and in particular the metallicity enrichment adopted will significantly modify the predicted CSED shape. Upcoming papers will explore these issues in more detail, but here we wish to construct a basic first-look model and focus on the viability of the hypothesis that galaxy formation progressed in two fairly distinct phases: rapid spheroid formation followed by more quiescent disc growth.

In order to construct a model of the present day spheroid and disc CSEDs we need not just the CSFH, but the CSFH subdivided into spheroids and discs. These CSED predictions can then be compared to the data from Section 2.

The existence of various SMBH–bulge relations (e.g. Ferrarese & Ford 2005) provides the obvious smoking gun, as it couples SMBH growth to bulge growth. This is because SMBHs are believed to grow via mergers, resulting in an AGN phase (Hopkins et al. 2006). The growth of spheroids is therefore, arguably, mirrored via the more readily observable AGN activity history. This logical connection, from a correlation to causality, is the key assumption underpinning our model and forms the first of our two axioms. In the recent study by Richards et al. (2006), the integrated AGN activity versus redshift was reported and, ignoring any significant lag (in either spheroid formation or AGN activity), can be used as a proxy in shape for the spheroid CSFH.

The amplitude of the spheroid star formation history (SFH) can be set from comparison of the AGN activity shape to the global CSFH. For our second axiom we elect to maximize the spheroid CSFH by setting the amplitude as high as possible without exceed-

ing the global CSFH (i.e. a maximal spheroid formation scenario). Conceptually then, the heart of the two-phase model can be defined empirically from two axioms:

- (1) AGN activity traces spheroid growth;
- (1) spheroid formation dominates at high- $z$ .

As the above two axioms are already constrained by empirical data, this provides a zero-parameter starting point for the two-phase model – bypassing the need for any initial conditions or detailed numerical simulations. Fig. 1 (upper) shows the fit (solid curve) to the CSFH data (grey data points) taken from Hopkins & Beacom (2006; see their fig. 2 a and table 1, column 2). This adopts the parametric form defined by Cole et al. (2001) and where the UV data have been calibrated to a modified Salpeter (1955) IMF. The data describing the AGN luminosity density are taken from Richards et al. (2006) and rescaled such that the peak of the AGN luminosity density lies on the CSFH curve (requiring an arbitrary multiplication by a factor of  $3.51 \times 10^6 M_{\odot} \text{ yr}^{-2} L_{\odot}^i$ ). Immediately noticeable is the apparent discrepancy/uncertainty at very high redshift. Particularly as the axioms above require that at the very highest redshift the CSFH and AGN activity curves should have the same form. To some extent the evident discrepancy simply reflects data uncertainty, as the dust corrections on the CSFH at high- $z$  are poorly constrained with significant ongoing debate as to the true shape of the CSFH at the highest redshifts. For example, measurements of the star formation history based on gamma-ray bursts (Yuksel et al. 2008; Kistler et al. 2009) often find higher star formation rates. Likewise the



**Table 1.** CSFH multiplication factors ( $\xi$ ) for various IMFs.

IMF	Multiplier $\xi$
Salpeter (1955)	$\times 1.3$
Modified Salpeter (Hopkins & Beacom 2006)	$\times 1.0$
Baldry & Glazebrook (2003)	$\times 0.7$
Kroupa (1993)	$\times 1.7$
Kroupa (2001)	$\times 0.85$
Chabrier (2003)	$\times 0.85$

incidence of dust-obscured AGN is an equally hotly debated topic (e.g. Polletta et al. 2006; Triester et al. 2010). Most recently Behroozi, Wechsler & Conroy (2013) argue that the compendium by Hopkins & Beacom (2006) potentially leads to an overestimate of the CSFH at very high redshifts as the pre-2006 UV luminosity densities may have been overestimated and find a modified CSFH which agrees very well with the high- $z$  AGN data (see their fig. 2).

When presented as a function of time (Fig. 1, lower), it is clear that this discrepancy is not actually that significant, and the accumulated stellar mass able to be formed during this high- $z$  interval is small compared to subsequent mass growth. We can now trivially fit the modified Richards data to derive the star formation history of spheroids. This fit can then be subtract from the global star formation history and in turn fit to recover the implied disc formation history. The resulting expressions are given below and represent the star formation rate ( $\dot{\rho}$ ) versus time in Gyr ( $t_{\text{Gyr}}$ ) since the big bang for the spheroidal (S) and disc (D) populations:

$$\dot{\rho}_S = \xi 1.03 \times 10^{-5} h_{0.7}^3 \left( \frac{21.86}{t_{\text{Gyr}} h_{0.7}} \right)^{8.57} \exp \left( -\frac{21.86}{t_{\text{Gyr}} h_{0.7}} \right), \quad (1)$$

$$\dot{\rho}_D = \xi 1.80 \times 10^{-3} h_{0.7}^3 \left( \frac{29.39}{t_{\text{Gyr}} h_{0.7}} \right)^{5.50} \exp \left( -\frac{29.39}{t_{\text{Gyr}} h_{0.7}} \right), \quad (2)$$

where  $\xi$  is the IMF multiplier as given in Table 1. The guideline error at any particular time should be taken as  $\sim \pm 25$  per cent based on the scatter of the original data shown in Fig. 1 (lower), i.e.  $\sim 70$  per cent of the grey data points lie on the grey shaded regions. At this point it is also worth highlighting that while the AGN data (mauve points) place a strong constrain on the shape of the spheroid star formation history the normalization is very uncertain and based on the relatively limited high- $z$  CSFH data and as we shall see in Section 4 will require a modest downward correction of 25 per cent to match the observed CSED (i.e. within the grey shaded error bounds).

As an alternative for the spheroid population, one could instead use the total CSFH for  $t < 3$  Gyr combined with the AGN luminosity density data for  $t > 3$  Gyr, which is given by

$$\dot{\rho}_{S2} = \xi 2.72 \times 10^{-4} h_{0.7}^3 \left( \frac{16.82}{t_{\text{Gyr}} h_{0.7}} \right)^{6.97} \exp \left( -\frac{16.82}{t_{\text{Gyr}} h_{0.7}} \right). \quad (3)$$

As stated these CSFHs are calibrated, via the UV data, to the modified Salpeter IMF used by Hopkins & Beacom (2006) which was first laid down as Sal A by Baldry & Glazebrook (2003). To convert to other IMFs one needs to *multiply* by the factor ( $\xi$ ) shown in Table 1. The simple expressions above are shown in Fig. 1 (lower) in red (spheroid), blue (disc) and green (spheroid + disc) and provide a good fit to the data given the accuracy to which the data are known. These equations now provide a blueprint for the formation of the present day spheroids and discs over the full age of the Universe,

leading to a clear prediction of the stellar energy output and stellar mass growth.

Of particular interest should be the transition point around 4.2 Gyr ( $z \approx 1.6$ ) from which point star formation resulting in disc growth dominates over star formation resulting in spheroid growth. This suggests a key epoch at which the Universe switches from merger-dominated evolution to accretion-dominated evolution and meshes very well with the evident change in the morphological appearance of galaxies from highly disturbed to more ordered systems at  $z \sim 1.5$  (see Driver et al. 1998; also see van den Bergh 2002).

## 4 CONSTRUCTING THE MODEL

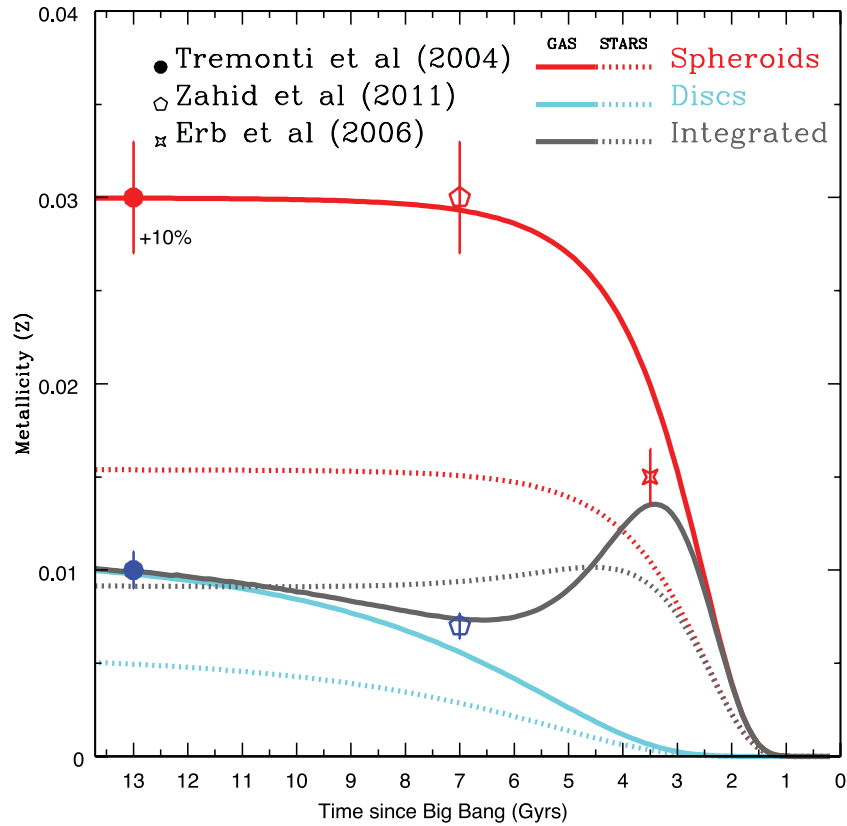
With the CSFH of spheroids and discs defined, we now build our empirical two-phase model adopting ‘vanilla’ choices at every opportunity. In summary the key inputs and assumptions to the model are the following.

- (1) The star formation history shown in Fig. 1 as discussed in Section 3.
- (2) The adoption of a Universal IMF, in this case Baldry & Glazebrook (2003, hereafter BG03).
- (3) The adoption of PEGASE.2 (Fioc & Rocca-Volmerange 1997, 1999) to model the spectral output of the evolving stellar population (using default options throughout).
- (4) The assumption that the gas-phase metallicity increases linearly with star formation from  $Z = 0.0$  to  $0.030$  for spheroids and to  $Z = 0.010$  for discs, with no time lag (i.e. instantaneous enrichment).

### 4.1 Metal/chemical enrichment history

Perhaps the most uncertain of the above list is the appropriate metallicity history to adopt. Here we have been guided by the study of Tremonti et al. (2004) to define our gas-phase metallicity at redshift zero to be  $Z = 0.030$  and  $0.010$  for the spheroids and discs. These values were determined by noting the metallicity at  $10^{11} M_{\odot}$  (predominantly spheroids) and at  $10^9 M_{\odot}$  (predominantly discs). To convert the given  $12 + \log_{10}(\text{O}/\text{H})$  values to those shown in Fig. 2 we adopt a solar metallicity of  $Z_{\odot} = 0.019$  with  $12 + \log_{10}(\text{O}/\text{H})_{\odot} = 8.9$ . We then argue that in the absence of other factors the mean metallicity will rise approximately linearly with the cumulative CSFH normalized to the present day values. This ignores the prospect of either pre-enrichment via, for example, Population III stars, or any lag between the star formation and the increase in metallicity (i.e. instantaneous enrichment).

Conceptually these are loosely consistent with a closed-box model for spheroids (i.e. rising to a metallicity close to typical yields), and an infall model for discs or one in which the disc is gradually growing from a large gas ‘reservoir’ (e.g. perhaps analogous to the ‘equilibrium model’ put forward by Davé, Finlator & Oppenheimer 2012). To explore the bounds and importance of this metal enrichment, however, we also show the CSED predictions using our simple evolving metallicity history and for constant metallicity at the highest and lowest values. Fig. 2 shows the implied metallicity histories derived from equations (1) and (2), for the two populations (as indicated by the red and cyan solid lines). Note that the grey lines in Fig. 2 show the combined metallicity of all stars formed (grey dotted line) and the integrated gas-phase metallicity (grey solid line). This shows interesting behaviour in that the average gas-phase metallicity (of the gas about to form stars) peaked at  $z \sim 2$ .



**Figure 2.** The adopted (gas-phase) metallicity for spheroids (red solid line) and discs (cyan solid line) as a function of time. Solid data points show the accepted mean  $z = 0$  values taken from Tremonti et al. (2004). Also shown are approximate data values from Erb et al. (2006) and Zahid, Kewley & Bresolin (2011). Note that all data have an arbitrary error of  $\pm 10$  per cent. The gas-phase metallicity assumes no lag between star formation and enrichment. The dotted lines show the implied metallicity of the stellar populations for the spheroids and discs. The grey line shows the mean by mass of the integrated stellar metallicity and the instantaneous integrated gas-phase metallicity.

Constraints from the literature on the mean metallicity at intermediate and high redshift are minimal, however, we note that Zahid et al. (2011) find from a sample of 1350 galaxies drawn from DEEP2 that massive systems have comparable gas-phase metallicity at  $z = 0.8$  to local systems, while low-mass systems have a gas-phase metallicity reduced by 0.15 dex. However, Erb et al. (2006) find that the implied gas-phase metallicity, for massive, i.e. spheroidal-like systems, at  $z \sim 2$  is approximately half that at  $z = 0$ . Both of these results are crudely consistent with our inferred metallicity history if one equates (as we explicitly do), the massive systems to spheroids and low-mass systems to discs. Note that one natural byproduct of this is that as intermediate-mass systems have both a spheroid and a disc component their systemic metallicity will lie somewhere between the two extremes and exhibit strong radial gradients as one moves from the central spheroid component to the outer disc component. As the mean bulge-to-total ratio increases fairly smoothly with stellar mass this naturally gives rise to the mass–metallicity relation (Tremonti et al. 2004). Note that the  $\pm 10$  per cent error ranges shown in Fig. 2 are purely indicative as the actual ranges are poorly constrained.

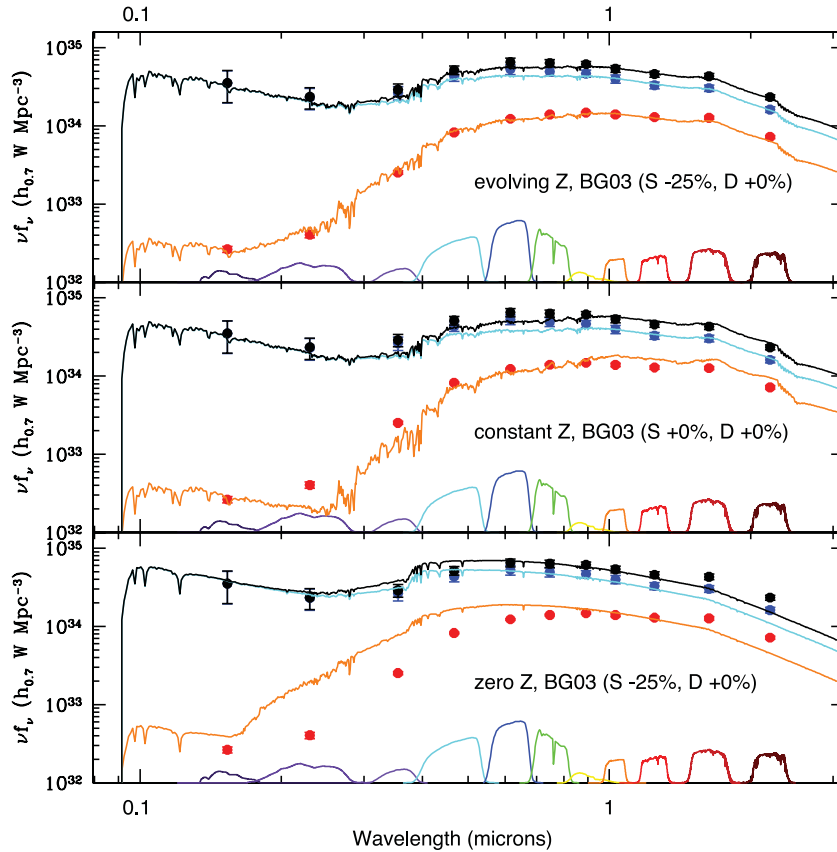
#### 4.2 Stellar population synthesis

To construct the redshift zero CSED the PEGASE.2 code (Fioc & Rocca-Volmerange 1997, 1999) was used to produce a series of single stellar population (SSP) templates with an appropriate range

of metallicities ( $Z = 0.000\text{--}0.025$  in 0.001 intervals) and with the PEGASE.2 default steps in ages (i.e. roughly logarithmic from 0 to 20 Gyr). For all SSP templates the star formation is set to a short continuous burst over a 1 Myr period with constant metallicity (leading to the formation of  $2.0 \times 10^{-3} M_{\odot}$  in PEGASE.2 normalized stellar mass units). These SSP spectra were then combined to create a library of 1 Gyr time averaged spectra from 0–1 to 13–14 Gyr in 1 Gyr intervals, and for each metallicity class. Note that the 0–1 Gyr bin which dominates the FUV and NUV region is extremely hard to model correctly because of the rapidly changing UV flux and requires more care. Here we take the rather simplistic approach of combining all the spectra provided by PEGASE.2 in the 0–1 Gyr range in the following manner, i.e.

$$0\text{--}1 \text{ Gyr} = \frac{\frac{1+2+3+\dots+10}{10} + \frac{20+30+\dots+100}{10} + 200+300+\dots+1000}{10} \text{ Myr.}$$

To create the CSED at any redshift we then sum all previously formed populations, aged appropriately, drawn from the appropriate metallicity class and scaled by the required star formation rate. The modelling approach we adopt is therefore relatively simplistic and effectively assumes all values (star formation rate, metallicity, etc.) are held constant over a 1 Gyr time period. At this stage we feel this is sufficient time resolution given the inherent uncertainties in the initial assumptions (i.e. the input CSFH and AGN activity data). CSEDs were then derived at all 13 time steps and combined to



**Figure 3.** The zero-parameter output, assuming a BG03 IMF for various metallicity histories as indicated and adopting the star formation histories given by equations (1) and (2). Note that the star formation rates have been multiplied by a factor of 0.55 to convert from a Salpeter (1955) IMF to that of BG03. The data points are transcribed directly from the CSED reported in Driver et al. (2012) where the red points represent spheroid dominated, the blue represent disc dominated and the black the sum of the two. The model lines are for spheroids (orange), discs (cyan) and the sum (black).

produce simple evolution movies available as supporting information from the journal's website.

### 4.3 Normalization of the CSEDs

In order to determine the correct normalization we need to multiply the output PEGASE.2 SSP spectra which are in units of  $\text{erg s}^{-1} \text{\AA}^{-1}$  by  $\frac{10^9 \lambda}{10^7 0.002}$ . Here the factor  $10^9$  scales to 1 Gyr bins, the factor  $10^7$  converts  $\text{erg s}^{-1}$  to W, the wavelength is in Angstroms, and the factor 0.002 scales the spectra to  $1 M_{\odot}$ . In applying equations (1)–(3) we set  $\xi$  to 0.7 to correct the CSFHs to the BG03 IMF.

Finally, we allow the normalizations to float by  $\pm 25$  percent to account for the uncertainty highlighted in Fig. 1 by the grey shading, along with uncertainties in the multiplication factors in Table 1, the cosmic variance in the GAMA CSED data and the impact of metallicity on star formation rates. These values are shown in brackets in Figs 3 and 4.

## 5 MODELS VERSUS DATA

### 5.1 The CSED and adopted metallicity

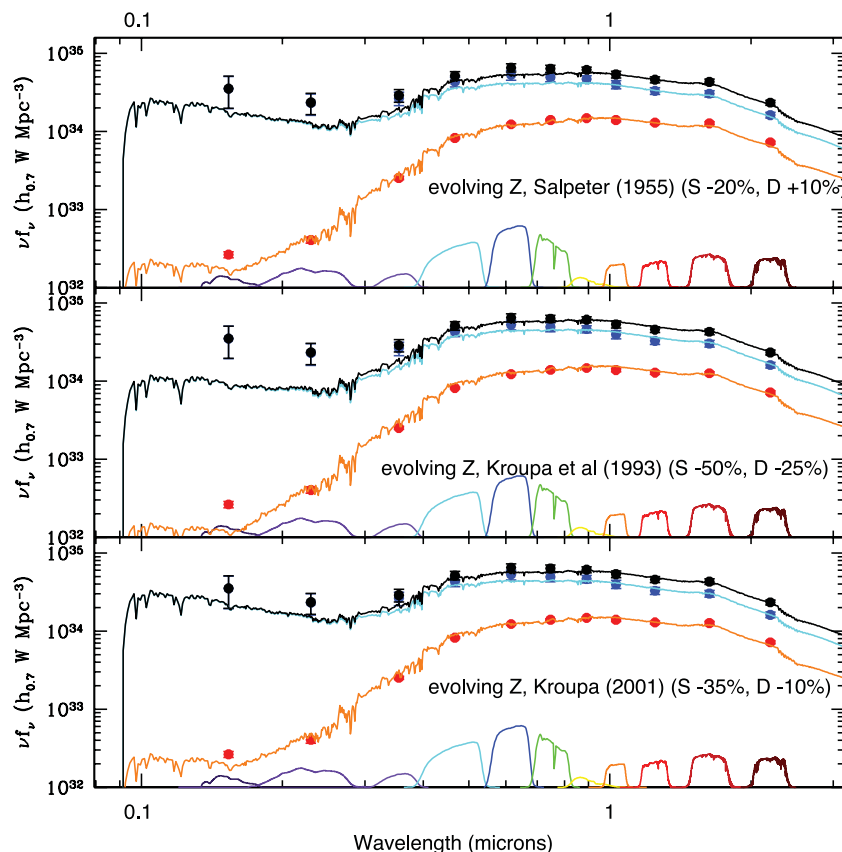
Fig. 3 shows the direct comparison of our  $z = 0$  CSED models against the recent GAMA data (Driver et al. 2012), for the three assumed metallicity histories (as indicated). The top panel,

which adopts the evolving metallicity, shows a remarkable agreement across the full wavelength range and for both the spheroid and disc systems. Note that in achieving these fits the spheroid data have been renormalized downwards by 25 per cent which is within the specified range of uncertainty. The central and lower panels of Fig. 3 show the same models except for a constant high or low metallicity. This has a negligible impact on the disc CSED, suggesting very little dependency on the assumed metallicity evolution for discs (perhaps in part due to the low value adopted). Conversely the impact on the spheroid CSED is quite marked with the CSED tilting either redward or blueward for constant high or constant low metallicity, respectively. This perhaps lends some argument against any very strong pre-enrichment phase as intermediate- and low-metallicity stars in spheroids are required to produce a plausible CSED. The obvious caveat is whether the shape of the currently adopted spheroid CSED is significantly modified/contaminated by young disc light.

### 5.2 Dependency on assumed IMF

We now briefly explore the impact of the adopted IMF. Fig. 4 shows the CSED predictions for the evolving metallicity scenario using either a (top) Salpeter (1955), (centre) Kroupa et al. (1993), (bottom) or Kroupa (2001) IMF. Note that the Kroupa (2001) IMF is extremely close in form to the Chabrier (2003) IMF and therefore the Kroupa (2001) prediction can be taken as representative of both.





**Figure 4.** The zero-parameter output for alternative IMFs using the evolving metallicity shown in Fig. 2 and adopting the star formation histories given by equations (1) and (2). Note that in generating the models we modify the input star formation by factors of  $\times 1.0$ ,  $\times 1.3$  and  $\times 0.7$ , respectively.

Essentially all IMFs provide an equally good fit to the CSED except in the UV regime. At wavelengths longer than  $u$  band ( $>0.4 \mu\text{m}$ ) the resulting shape is not particularly sensitive to the detailed shape of the IMF. This is mainly because at  $z = 0$  stars close to solar luminosity, where the IMF is least contentious, are dominating most of the CSED. Systems at the very high-mass end which formed at high redshift will no longer be contributing to the CSED whereas very low-mass stars are yet to dominate the near-IR flux. The CSED is therefore unable to constrain the IMF other than the normalizations required for these IMFs are generally higher than for the models based on BG03.

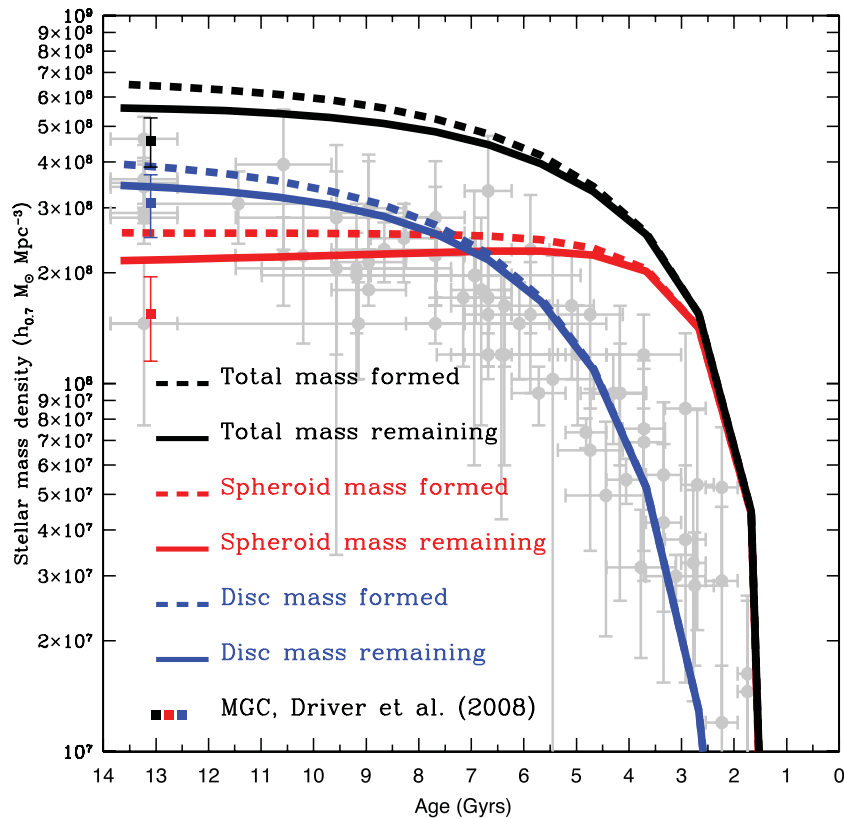
### 5.3 Stellar mass history

Fig. 5 shows the implied build-up of stellar mass in spheroids and discs (and combined), as indicated. Note that we show both the total cumulative stellar mass formed (dashed lines), along with that remaining based on default PEGASE.2 assumptions as to mass loss (solid lines). Also shown are the direct empirical stellar mass measurements from the MGC (Liske et al. 2003; Driver et al. 2005), which includes corrections for dust attenuation (Driver et al. 2008). The agreement is reasonable with the discs agreeing with the MGC data to within the error and the spheroid mass overpredicting the MGC value by a modest amount. It is worth noting from Fig. 5 that the stellar mass of spheroids is actually declining, with mass loss having exceeding mass gain for the past nine billion years. For the discs, the two almost exactly balance, such that the overall stellar mass density appears to asymptote to a constant value around the present day.

Also shown in Fig. 5 as grey shaded data are the compendium of total stellar mass estimates given in Wilkins et al. (2008a). These data clearly fall significantly below the black shaded line, highlighting a significant discrepancy between the total stellar mass inferred from the CSFH and that derived from direct empirical constraints. This offset is well known and discussed in detailed in Wilkins et al. (2008a), here we make two additional comments: (1) the shape of the data and the black curve do broadly agree with a  $\times 2$  offset at almost all ages, (2) the  $z = 0$  data from the MGC includes detailed dust corrections for both the optically thin *and* optically thick regions and is typically a factor of  $\times 2$  higher than most local measurements. It is possible then that the values from the literature are missing mass embedded in optically thick regions. Perhaps a more likely explanation, also put forward by Wilkins et al. (2008b) is that the IMF was simply lighter at earlier times. This would reconcile quite nicely as the low- $z$  CSED is fairly impervious to the very low mass end of the IMF.

### 5.4 Discussion

At this point we have a simple heuristic model which adopts two simple axioms motivated by the physically distinct appearance of spheroids and discs in the nearby Universe. These axioms combined with the empirical compendium of AGN and cosmic star formation activity/history are able to reproduce the  $z = 0$  CSEDs of spheroids and predict the mean mass and metallicity evolution of present day discs and spheroids. The model also provides a complete description of the energy output from stars within those systems which will eventually make up the local spheroid population (progenitors) as a



**Figure 5.** The implied build-up of stellar mass in spheroids and discs versus recent measurements from the MGC. Shown in grey are the compendium of data from Wilkins, Trentham & Hopkins (2008a).

function of redshift, the metallicity build-up and suggests key cross-over epoch at  $z \sim 1.6$  between the hot and cold mode evolution. This later transition redshift is consistent with the obvious change in morphologies seen in *Hubble Space Telescope* (HST) images at this redshift (e.g. Driver et al. 1998, fig. 3).

However an obvious weakness is that the model provides no clear prediction of the morphological, size and shape evolution, merger rates or the clustering of the galaxy population. Furthermore, the model does not stipulate the actual mechanism by which star formation is occurring and for the hot mode could be some combination of monolithic collapse, major merging and/or clump migration. Within the recent literature the exact status of the  $z \sim 2$  population is also unclear. Deep integral field unit (IFU) studies (e.g. Forster Schreiber et al. 2009, 2011) find that the majority of star formation at  $z \sim 2$  appears to be taking place in rotating clumpy disc structures with no obvious central bulge component. Similarly, Chevance et al. (2012, see also Weinzierl et al. 2011) from a study of 31 high- $z$  galaxies, find that the Sérsic indices are significantly flatter than one would expect for low- $z$  spheroids and obvious disc structures are present in many cases. From our Fig. 1 we can see that at  $z \sim 2$  we are still within the epoch where spheroid formation should be dominating. However spheroid formation does not necessarily imply spheroid morphologies until after some unspecified time lag in which the system settles. In fact violently star-forming systems will inevitably appear blue, asymmetrical, gas rich and dusty, i.e. quite disc like in many aspects. Other studies, e.g. van Dokkum et al. (2008), find that 45 per cent of massive galaxies at  $z \sim 2.3$  do indeed have evolved stellar populations, little or no ongoing star formation and compact early-type morphologies. Hence a picture of a spheroid population emerging from a highly turbulent

progenitor phase around  $z \sim 2$  appears to be qualitatively consistent with our model. Alternatively our model may need to be adjusted to allow for gas infall and disc formation from the outset with some fraction of the disc-formed stars merging into bulges, i.e. a relaxation of the maximal spheroid formation axiom. This would have the net effect of also increasing the cross-over redshift to  $> 1.6$ .

A further intriguing observation is that high- $z$  spheroids are significantly more compact than nearby ellipticals by factors of  $\times 3$ – $4$  at fixed stellar mass (e.g. Daddi et al. 2005; van Dokkum et al. 2008, etc.). Within our scenario this could be consistent with the high- $z$  sample being ‘naked’ bulges yet to grow discs or yet to be ‘puffed-up’ through successive minor merger interactions or adiabatic expansion. These two pathways, disc growth versus ‘puffing’, are likely to be strongly environmentally dependent with minor mergers more frequent in high-density environments, and gas infall more prevalent in low-density environments. A particularly interesting comparison might therefore be the mass–size relation of high- $z$  spheroids to low- $z$  bulges.

With the caveat that the morphology and size evolution within our model is unspecified we nevertheless appear to have a prediction of the energy output of spheroid and discs progenitors over all epochs (Fig. 3, top panel), the mean gas-phase metallicity history for each population (Fig. 2), and the build-up of stellar mass (Fig. 5). Whether one can readily distinguish these populations observationally however is an open question.

Finally, it is worthwhile reiterating that this model contains *no tunable parameters nor any dependency on initial conditions beyond the underlying cosmology*. The model is built entirely from empirical data and provides a fully consistent empirical scaffolding upon which more physically motivated models can be built.

Our conclusion is that the initial axioms on which the model is based are viable and the star formation histories defined are tenable.

Further studies of the variation of the  $z = 0$  CSED and its dependency on environment should enable an investigation into dependencies on clustering, and to assess whether star formation proceeds more rapidly or whether it is merely the relative mix of spheroid versus disc formation which is changing. Similarly, using observations at intermediate redshift, it should be possible to compare data from high- $z$  studies to the predictions of our two-phase model. Both of these avenues will be explored in future papers.

## 6 CONCLUSIONS

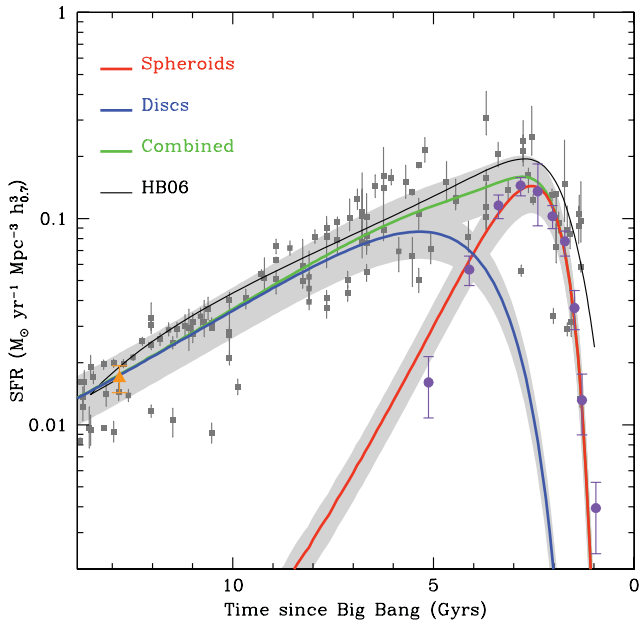
From two very simple axioms: (1) that AGN activity traces spheroid formation, and (2) that the CSFH is dominated by spheroid formation at high redshift, we are able to derive simple expressions for the CSFHs of spheroids and discs. Following comparisons to the  $z = 0$  CSED for spheroids and discs we find a modest downward adjustment of 25 per cent provides the optimal fit resulting in our final recommended star formation histories of

$$\dot{\rho}_S = \xi 0.77 \times 10^{-5} h_{0.7}^3 \left( \frac{21.86}{t_{\text{Gyr}} h_{0.7}} \right)^{8.57} \exp \left( -\frac{21.86}{t_{\text{Gyr}} h_{0.7}} \right), \quad (4)$$

$$\dot{\rho}_D = \xi 1.80 \times 10^{-3} h_{0.7}^3 \left( \frac{29.39}{t_{\text{Gyr}} h_{0.7}} \right)^{5.50} \exp \left( -\frac{29.39}{t_{\text{Gyr}} h_{0.7}} \right), \quad (5)$$

where  $\xi$  is the IMF multiplier as given in Table 1. Fig. 6 shows these final relations compared to the compendium of data provided by Hopkins & Beacom (2006) and despite the renormalization of the spheroid star formation history still provide a perfectly satisfactory description of the global CSFH.

Adopting a BG03 IMF and using these expressions to predict the  $z = 0$  CSED, we are able to provide a satisfactory explanation of the observed CSEDs of spheroids and discs from the FUV to the  $K$  band.



**Figure 6.** As for Fig. 1 (lower) except with the spheroid star formation history down weighted by 25 per cent by incorporating the CSED constraints from Fig. 3 (upper).

The corollary of the simplicity of the two-phase model, however, is that it lacks any prediction of the clustering signature, environmental dependencies or the merger histories, although these can be built in at a later stage. Perhaps the key gain, in an era of hidden tunable parameters, is that with the adoption of a universal IMF and a stellar evolution code there are essentially no free parameters. Strictly speaking this is not precisely true as the detailed modelling of stellar evolution typically comes with options and there is arguably a choice of IMFs and also whether it is Universal or varies over cosmological time (see e.g. Wilkins et al. 2008a,b; Gu-nawardhana et al. 2011). On this last subject of the IMF it is worth reiterating that longward of  $0.4 \mu\text{m}$  the  $z = 0$  CSED is not sensitive to the high-mass shape of the IMF (unless taken to the extreme). This is because at almost all wavelengths, in the declining star formation era today, the CSED is dominated by either the tip of the main sequence, which lies just below a solar mass and well above the mass range of contention (mid-optical to near-IR), or the most recently formed stars (FUV to mid-optical).

As a byproduct, the two-phase model also provides the CSED of spheroids and discs at every epoch in the Universe, along with the prediction of a clear-cut transition redshift at around  $z \approx 1.7$  where galaxy evolution switches from evolution being dominated by major mergers to evolution being dominated by cold gas infall. Future work will include a broader wavelength baseline, bulge-disc decompositions, inclusion of the asymptotic giant branch (AGB) energy output and development of the model via comparisons to selected external data.

## ACKNOWLEDGEMENTS

We thank the referee for insightful comments during the refereeing process which has helped improve the paper.

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## SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

**Model 1.** Evolving metallicity

**Model 2.** Constant high metallicity

**Model 3.** Constant zero metallicity

(<http://mnras.oxfordjournals.org/lookup/suppl/doi:10.1093/mnras/sts717/-/DC1>).

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